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Loss analysis of single mode telecommunication fiber thermally-diffused core areas

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In this work, diffusion processes in thermally connected cylindrical fibers with weakly guiding and circular cross-section, that is, telecommunication fibers, have been presented. There have been discussed diffusion distributions of the core dopant of fibers spliced at $T \approx 2000$ °C. Gaussian approximations of the core dopant concentration distribution and refractive index in the connecting area of single mode telecommunication fibers have been presented. Theoretical analysis of propagation and loss characteristics for thermally-diffused expanded core (TEC) of single mode telecommunication fibers has been performed, as well. Consistence of theoretical calculation results with experimental data, achieved on the basis of connecting telecommunication fibers with significantly different parameters, has been proved.

Keywords: single mode fibers, thermally-diffused expanded core (TEC), dopant distribution, refractive index profile, Gaussian approximation.

1. Introduction

Waveguide fibers are very thin in relation to their length. If in these types of fibers refractive index coefficients of the core (n_r) and cladding (n_p) differ insignificantly they are considered weakly guiding. Waveguide fibers with weakly guiding and circular symmetry are called telecommunication fibers.

Optimization of spliced joints of telecommunication fibers of different types involves thermal diffusion of the connected fibers core dopant (most often GeO_2) in such a way that the mode field radii in the thermally-diffused expanded core (TEC) – the splice intermediate area, will equalize [1]. It can be proved that this area with length $2L$ (Fig. 1) retains its single mode character as the amount of dopant in the process of thermal diffusion remains the same [2]. Normalized frequency V in the transit area is smaller than 2.405.

The present work aims at an analysis of diffusion processes within the splice, their approximation by Gaussian distributions, and evaluation of diffusion optimal times,

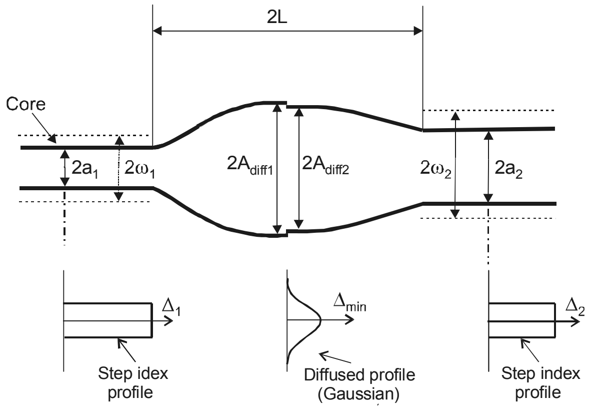

Fig. 1. Schematic illustration of thermally-diffused expanded core of connected fibers splice.

as well as mainly theoretical analysis of losses occurring in the transit area resulting from mismatch between the mode fields and TEC area dimensions, and finally, comparison of the analysis results with experimental data.

2. Diffusion processes in the transit area of the connected fibers

Proper matching of mode field diameters (MFD) within the thermal joint of telecommunication fibers of different types reduces considerably loss of such joints [3, 4]. Matching is the result of the core dopant thermal diffusion.

Diffusion coefficients D of the core dopant GeO_2 in SiO_2 for $T \approx 2000$ °C presented in [3] were in the range $D = 10^{-11}$–10^{-10} m^2/s. However, approximating the values of $D(T)$ taken from [5] for $T \approx 2000$ °C yielded $D = 5\times10^{-13}$–10^{-12} m^2/s, and these were accepted in the present work.

In Figures 2 and 3, diffusion distributions are presented, with their Gaussian approximation of GeO_2 concentration in SiO_2 being given for five splice times: $t_1 = 2$ s, $t_2 = 3$ s, $t_3 = 5$ s, $t_4 = 7$ s, $t_5 = 10$ s, and fusion splicing temperature $T = 2000$ °C.

For distributions of Fig. 2, there was assumed the diffusion from a layer with limited thickness (core diameter) [6], that is, $h = 2a = 8$ μm, dopant concentration (before diffusion) $N_0 = 6.79\times10^{26}$ m^{-3} (3.1 at%), which corresponds to the refractive index coefficient in the core $n_r = 1.45149$, and the refractive index coefficient in the cladding (undoped SiO_2) was $n_p = 1.44680$, with n_r and n_p calculated using the Sellmeier formula [7]. The above parameters correspond to the standard single mode telecommunication fiber with step refractive index profile (SI SMF) G.652 [8] with $\Delta\% = [(n_r^2 - n_p^2)/2n_r^2]\times100\% = 0.32\%$ and numerical aperture NA = 0.116 (calclations were made for $\lambda = 1.31$ μm). For calculation purposes, a diffusion coefficient $D = 5\times10^{-13}$ m^2/s was accepted.

For distributions of Fig. 3, also the diffusion from a layer with limited thickness [6] was assumed, but the core thickness was $h = 2a = 6$ μm, dopant concentration (before diffusion) $N_0 = 1.27\times10^{27}$ m^{-3}, which corresponds to the refractive index coefficient in the core $n_r = 1.45569$, and the refractive index coefficient in the cladding (undoped SiO_2) was $n_p = 1.44680$ (n_r and n_p were calculated with the use of the Sellmeier formula [7]). The above parameters correspond to single mode telecommunication fibers with step refractive index profile SI SMF of type G.653 or G.655 [9, 10] with Δ% = 0.61% and numerical aperture NA = 0.161 (the calculations were made for $\lambda = 1.31$ μm). In this case, diffusion coefficient $D = 10^{-12}$ m^2/s was accepted as along as with higher dopant concentrations an increase of the diffusion coefficient can be observed [11, 12].

Diffusion distributions were calculated with the use of an expression of diffusion from a layer with limited thickness (core diameter) $h = 2a$:

$$N(r, t) = \frac{N_0}{2}\left[\operatorname{erf}\left(\frac{r+h}{2\sqrt{Dt}}\right) - \operatorname{erf}\left(\frac{r}{2\sqrt{Dt}}\right)\right] \tag{1}$$

where: N_0 – core dopant concentration before diffusion, h – layer thickness (core diameter), D – diffusion coefficient, t – diffusion time, r – distance from the core center.

Gaussian distributions were calculated using the expression:

$$N(r, t) = N_0(0, t)\exp\left(\frac{-r^2}{A_{\text{diff}}^2}\right) \tag{2}$$

here: $N_0(0, t)$ – concentration in the core center decreasing with time, A_{diff} – the core diameter after diffusion where the dopant concentration decreases by e times $A_{\text{diff}}^2 = a^2 + 4Dt$.

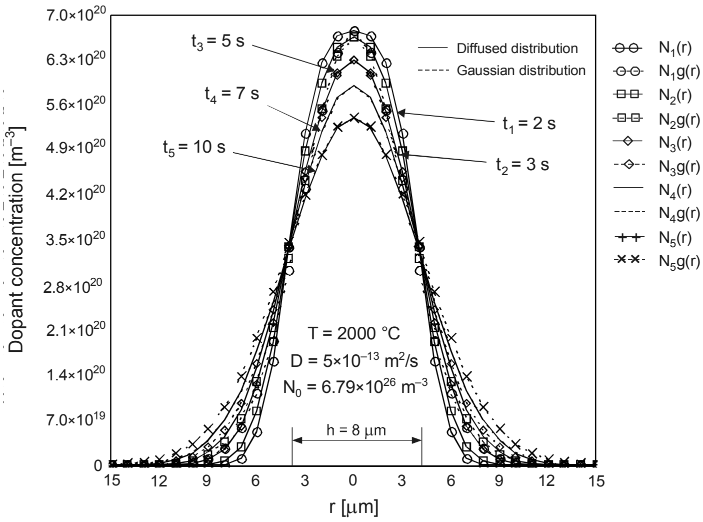

Fig. 2. Dopant diffusion distributions and their Gaussian approximation for SI SMF of G.652 type.

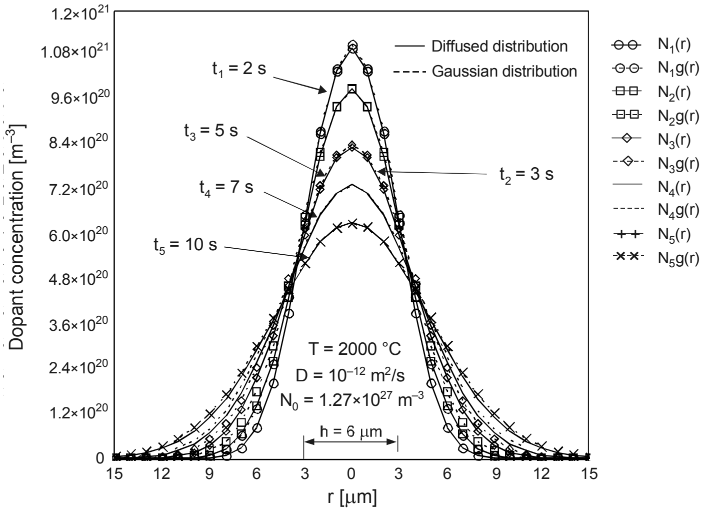

Fig. 3. Dopant diffusion distributions and their Gaussian approximation for SI SMF of G.653 or G.655 type.

A good consistency of diffusion and Guassian distributions was found, which were the better the longer the diffusion time and the greater diffusion the coefficient (Figs. 2 and 3).

2.1. Refractive index profiles

It is obvious that refractive index profiles reflect well the dopant distributions. Gaussian function describes well the fundamental mode field distribution LP_{01} for the step refractive index profile [13, 14]. Attempts were made to describe the fundamental mode field distribution LP_{01} for fibers with random profile of refractive index by the Gaussian function [13–15]. It turns out that the Gaussian approximation of field distributions which significantly simplifies calculations of the connected fibers losses, is specially useful in the cases of refractive index profiles for which there is no analytic solution of a scalar wave equation [15]. Gaussian profile of refractive index is such an example. This form of profile is of great practical importance as, first of all, it reflects diffusion processes of dopants between the core and the cladding in the production process of fibers, and besides, it is possible to approximate refractive index distributions in the transit area of thermally connected telecommunication fibers of different types.

Values of GeO_2 concentration were assigned corresponding values of refractive index coefficient, calculated using the Sellmeier formula [7]:

$$n^2 = 1 + \sum_1^3 \frac{a_i \lambda^2}{\lambda^2 - b_i^2} \tag{3}$$

T a b l e 1. GeO_2 doped levels of the core and equivalent values of refractive index for $\lambda = 1.31$ μm.

Dopant concentration [at%]	0	3.1	5.8	7.9	13.5
Dopant concentration [m^{-3}]	0	6.79×10^{26}	1.27×10^{27}	1.73×10^{27}	2.95×10^{27}
Refractive index n_r	1.44680	1.45149	1.45568	1.45904	1.46807

where a_i and b_i (in micrometers) are constants determined experimentally for different dopants and doped levels.

Examples of the levels of GeO_2 doping and the corresponding refractive indices in the core are presented in Tab. 1.

Dopant distribution after diffusion is consistent with Gaussian distribution, which leads to Guassian distribution of the refractive index:

$$n^2(r) = n_p^2 + \left(n_r^2 - n_p^2\right)\exp\left(\frac{-r^2}{A_{\text{diff}}^2}\right) \tag{4}$$

where: n_r is the value of the refractive index in the core center ($r = 0$) after diffusion, A_{diff} is the core diameter calculated as half width on the height $1/e$ from the dopant maximum concentration $A_{\text{diff}} = \sqrt{a^2 + 4Dt}$.

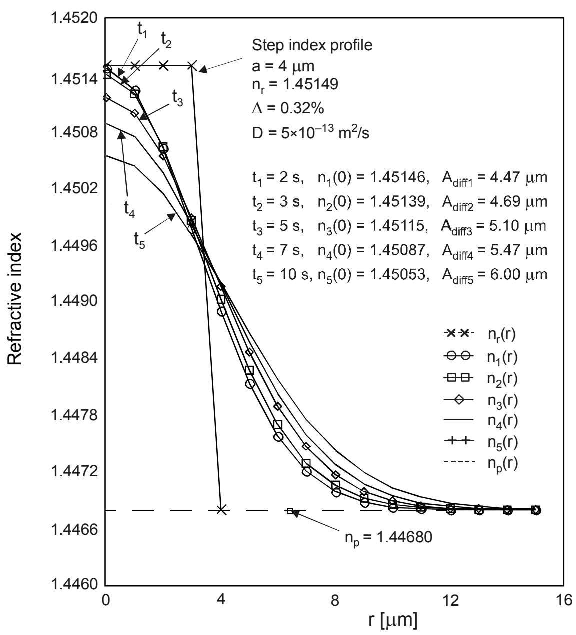

Fig. 4. The core refractive index profiles in SI SMF of G.652 type for five diffusion (splicing) times, $\lambda = 1.31$ μm.

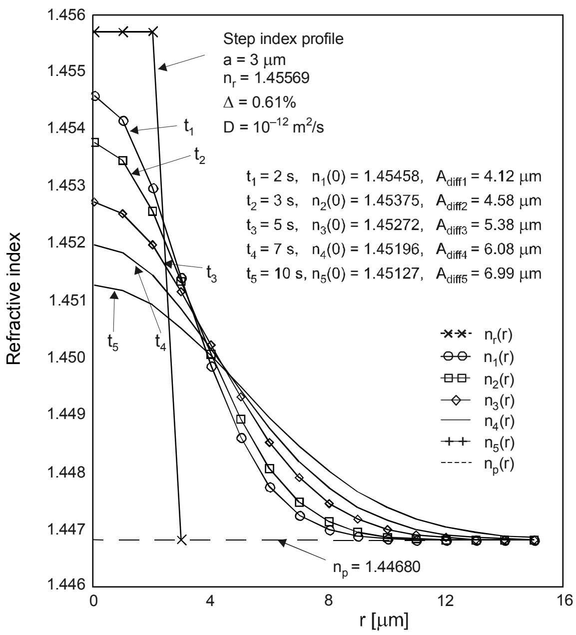

Fig. 5. The core refractive index profiles in SI SMF of G.653 or G.655 type for five diffusion (splicing) times, $\lambda = 1.31$ μm.

Refractive index profiles for five diffusion times (splicing), calculated according to expression (4) and corresponding to the dopant distributions of Figs. 2 and 3 are presented in Figs. 4 and 5.

2.2. Matching mode field radii

Optimization of the process of thermally connecting telecommunication fibers with different parameters, involves matching mode fields of the connected fibers by a method of diffusing the core dopant [3] and minimizing the TEC area loss, see Fig. 1.

Figure 1 shows an ideal optimization when the dopant diffusion in the area of splice caused equalization of the dopant concentration and the core diameters in the connection place. This means equalization of the mode fields. It is possible at the same temperature and heating (splicing) time as for a higher dopant concentration (smaller core diameter) the diffusion coefficient is of higher value [11, 12].

However, if the mode fields of the connected fibers are not totally equalized, then, apart from transmission losses of TEC area, there also occur losses *A* due to mismatch of the mode fields (see Eq. (5)). With the assumption that the fundamental mode field distribution LP_{01} can be approximated with the Gaussian distribution, which is true for step and Gaussian refractive index profiles [1, 15, 16], we obtain:

$$A = -10\log\left[\left(\frac{2\omega_{\text{diff1}}\,\omega_{\text{diff2}}}{\omega_{\text{diff1}}^2 + \omega_{\text{diff2}}^2}\right)^2\right] \tag{5}$$

where ω_{diff1}, ω_{diff2} are the mode field radii of the connected fibers in the connection place (here, after diffusion, though the formula is of general character), in TEC.

The practice of splicing connecting fibers with significantly different parameters, *e.g.*, G.652 and G.655, indicates that it is possible to arrive at a loss in those fibers lower than 0.1 dB [17] using dopant diffusion within the splice (TEC).

It is optimal, however, to rely on calculations, thus with the above given diffusion coefficients and thermal connecting temperature it is advisable to match optimal splicing times after diffusion on the basis of the core radius values, mode fields radii and TEC transmission parameters.

In Tables 2 and 3, the calculated values of the core and mode field radii for different diffusion times and two wavelengths $\lambda = 1.31$ μm and $\lambda = 1.55$ μm, for fibers G.652 and G.655, are presented. For the Gaussian mode field distribution LP_{01} [5, 16]: radii of the mode field before diffusion $\omega = a/\sqrt{\ln V}$, where a – core before diffusion, and because $V = (2\pi/\lambda)a\text{NA}$ remains constant after the diffusion process [2, 15], then, $\omega_{\text{diff}} = A_{\text{diff}}/\sqrt{\ln V}$. For the accepted G.652 fiber parameters, $V = 2.23$ for $\lambda = 1.31$ μm, and $V = 1.88$ for $\lambda = 1.55$ μm. Whereas, for G.655, $V = 2.32$ for $\lambda = 1.31$ μm, and

Table 2. Values of A_{diff}, ω_{diff} and $\gamma_{\max}$ for different diffusion times in G.652, $a = 4$ μm, $\omega = 4.66$ μm for $\lambda = 1.31$ μm and $\omega = 5.53$ μm for $\lambda = 1.55$ μm.

Diffusion time [s]	A_{diff} [μm]	ω_{diff} (for $\lambda = 1.31$ μm) [μm]	$\gamma_{\max} = A_{\text{diff}}/a$	ω_{diff} (for $\lambda = 1.55$ μm) [μm]
2	4.47	4.99	1.12	5.62
3	4.69	5.23	1.17	5.90
5	5.10	5.69	1.27	6.42
7	5.47	6.11	1.37	6.88
10	6.00	6.70	1.5	7.55

Table 3. Values of A_{diff}, ω_{diff} and $\gamma_{\max}$ for different diffusion times in G.655, $a = 3$ μm, $\omega = 3.36$ μm for $\lambda = 1.31$ μm and $\omega = 3.98$ μm for $\lambda = 1.55$ μm.

Diffusion time [s]	A_{diff} [μm]	ω_{diff} (for $\lambda = 1.31$ μm) [μm]	$\gamma_{\max} = A_{\text{diff}}/a$	ω_{diff} (for $\lambda = 1.55$ μm) [μm]
2	4.12	4.49	1.37	5.02
3	4.58	4.99	1.52	5.58
5	5.38	5.86	1.79	6.55
7	6.08	6.62	2.03	7.41
10	6.99	7.62	2.33	8.52

Table 4. Loss of the TEC area, for different diffusion times, due to the mismatch of mode fields.

Diffusion time [s]	A (λ = 1.31 μm) [dB]	A (λ = 1.55 μm) [dB]
2	0.048	0.053
3	0.0096	0.013
5	0.0038	0.0017
7	0.028	0.024
10	0.072	0.063

V = 1.96 for λ = 1.55 μm. The core and mode field dimensions before diffusion for G.652 are: a = 4 μm, ω = 4.66 μm for λ = 1.31 μm and ω = 5.53 μm for λ = 1.55 μm, and for G.655: a = 3 μm, ω = 3.36 μm for λ = 1.31 μm and ω = 3.98 μm for λ = 1.55 μm.

The values ω_{diff} presented in Tabs. 2 and 3 indicate that splicing times of fibers G.652 and G.655, at T = 2000 °C, optimal for equalization range from 3 to 7 seconds. Then, the losses of TEC area resulting only from the mismatch of mode field radii (5) are the smallest. In Table 4, losses in the TEC area for different splicing times due to the mismatch of mode field radii are presented.

Total losses of the TEC area are the sum of losses due to the mismatch of the mode field radii and the transit area size, that is, first of all, its length $2L$ and $\gamma_{\max}$. Analysing these two components makes it possible to match the optimal thermal connecting time. It should be emphasized that connecting the analyzed fibers without diffusion results in a big splice loss (see Eq. (5)) A = 0.457 dB for λ = 1.31 μm and A = 0.465 dB for λ = 1.55 μm.

3. Analysis of the transit area transmission properties of the spliced fibers

Even with the assumption of an ideal matching of ω_{diff1} and ω_{diff2} there will still occur the TEC transmission losses [2, 5, 15].

Transmission power coefficient of the TEC for the general propagation beam model [5] expressed by:

$$T_p = \frac{\left|\int_0^\infty E_o(r) E_i^*(r) r \mathrm{d}r\right|^2}{\left[\int_0^\infty \left|E_i(r)\right|^2 r \mathrm{d}r\right]^2} \tag{6}$$

here, $E_i(r)$ is the field electrical component in the input TEC, $E_o(r)$ is the field electrical component in the output TEC.

T a b l e 5. Length L_c as a function of diffusion time.

Diffusion time [s]	L_c (G.652) [μm]	L_c (G.655) [μm]
2	27.7	28.1
3	33.7	35.0
5	44.3	46.9
7	53.8	56.9
10	65.4	69.3

Dependency curves $T_p(L, \gamma_{\max})$ [5] show the maximum for the TEC area characteristic length L_c:

$$L_c = \left[\gamma_{\max}(\gamma_{\max} - 1)\right]^{1/2} \frac{\pi n_r \omega}{\lambda} \tag{7}$$

Splicing fibers of the same type has been assumed here, that is, with the same n_r and ω (parameters before diffusion), Fig. 6. Lengths L_c as a function of diffusion time ($\gamma_{\max} = A_{\text{diff}}/a$) for fibers G.652 and G.655 are presented in Tab. 5.

Loss of the transit area is of course lower than the maximum if its length $L > L_c$ or $L < L_c$, and significantly smaller if $L \gg L_c$ or $L \ll L_c$ [5]. When the TEC area length is $L \gg L_c$ or $L \ll L_c$ (Fig. 6), then the transmission loss is negligibly small, which is the most desirable case for optimization of thermal fibers connecting process, *e.g.*, fusion splicing. The choice of temperature and thermal connecting times in such a way that good matching of the mode field radii and simultaneously the smallest losses connected with TEC dimensions are due to occur, finishes the process of thermal connecting optimization.

The fact that loss is small if $L \gg L_c$ or $L \ll L_c$ causes that the transmission losses in TEC area can be described by two different processes – transmission models. When

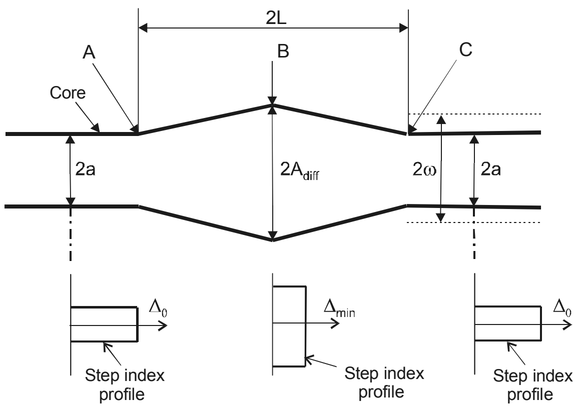

Fig. 6. Linear TEC area with a step refractive index profile – joining fibers of the same type.

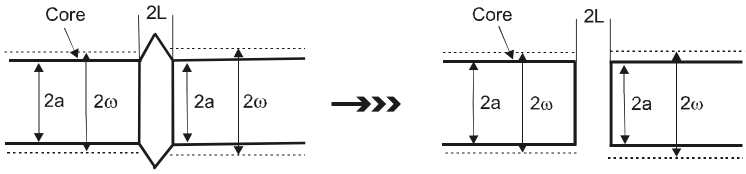

Fig. 7. Short area TEC and its equivalent model.

$L \ll L_c$ the transit area is an equivalent of the gap (Fig. 7) between connected fibers [4, 5], when $L \gg L_c$ a phase front transformer model is used [5, 15].

3.1. Gap model

With a simplified assumption of connecting the same type of fibers and an assumption that the transit area changes linearly, *i.e.*, the refractive index profile remains of step character and the core diameter changes linearly (normalized frequency remains stable in the TEC area) – Fig. 7 based on the gap model [4], the transmission coefficient of the TEC area can be expressed by:

$$T_g = \left[1 + \left(\frac{\lambda L}{\pi n_r \omega^2}\right)^2\right]^{-1} \tag{8}$$

The loss $-10\log T_g$ of the TEC area as a function of length L for a gap model and joints G.652-G.652 with parameters accepted in the work, is presented in Fig. 8. The loss in this model does not depend on $\gamma_{\max}$. This means that it does not depend on the diffusion

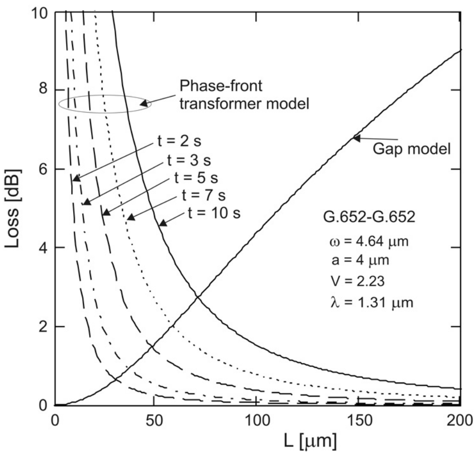

Fig. 8. Loss of the TEC as a function of length L for joining the same type of fibers (G652-G.652) for the gap model and the phase-front transformer model.

time and temperature during thermal fiber connecting. If we assume $L \to 0$, *i.e.*, $T_g \to 1$, then while connecting fibers with different ω, there will occur independently diffusion, big losses resulting from the mismatch of $A = -10\log\left\{\left[2\omega_1\omega_2/(\omega_1^2+\omega_2^2)\right]^2\right\}$ – fibers "see" each other without the TEC area, Fig. 7. Thus, optimization of losses due to different ω is practically impossible, which does not comply with experimental data [1]. So, the model is useless in the case of optimization by thermal diffusion method. Therefore, it is necessary to conduct the diffusion process so that the TEC area length will be $L \gg L_c$.

3.2. Phase-front transformer model

Under simplified assumptions of connecting fibers of the same type and linear transformation of the transit area, *i.e.*, the refractive index distribution retains its step character and the core diameter changes linearly, then based on a phase-front transformer model [5,15], the TEC area transmission coefficient (Fig. 6) can be written as:

$$T_f = T_A T_B T_C \tag{9}$$

here,

$$T_A = T_C = \left\{1+\left[\frac{1}{2}(\gamma_{\max}-1)\frac{\pi n_r \omega^2}{\lambda L}\right]^2\right\}^{-1} \tag{10}$$

$$T_B = \left\{1+\left[\gamma_{\max}(\gamma_{\max}-1)\frac{\pi n_r \omega^2}{\lambda L}\right]^2\right\}^{-1} \tag{11}$$

T_A, T_B and T_C are optical power transmission coefficients at points A, B, C (see Fig. 6).

Loss T_f of the TEC area as a function of length L, for a phase-front transformer and G.652-G.652 joints models with parameters accepted in this work, and five diffusion times are shown in Fig. 8; L_c can be defined approximately from the intersection of curves $T_f(L)$ and $T_g(L)$.

In the case of connecting fibers of different types the core dopant diffusion process should be conducted in such a way that equalization of the mode field radii is due to occur (in our case, at $T = 2000$ °C, best for diffusion times from 3 to 7 seconds) and so that the transmission coefficient should be the highest.

Assuming the mode field radii equalization and linear change of the transit area, *i.e.*, refractive index distribution retains its step character and the core diameter

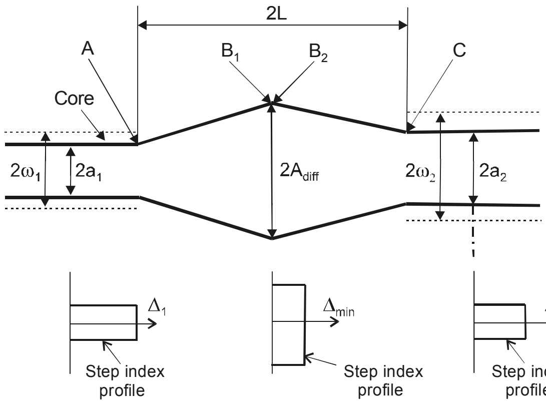

Fig. 9. TEC linear area with a step refractive index profile – joining fibers of different types.

changes linearly (Fig. 9), the lowest value of transmission coefficient T_f – the highest loss of the transit area – will be achieved, T_f being presented in the form:

$$T_f = T_A T_{B1} T_{B2} T_C \tag{12}$$

here,

$$T_A = \left\{ 1 + \left[\frac{1}{2}(\gamma_{\max 1} - 1) \frac{\pi n_{r1} \omega_1^2}{\lambda L} \right]^2 \right\}^{-1} \tag{13}$$

$$T_C = \left\{ 1 + \left[\frac{1}{2}(\gamma_{\max 2} - 1) \frac{\pi n_{r2} \omega_2^2}{\lambda L} \right]^2 \right\}^{-1} \tag{14}$$

$$T_{B1} = \left\{ 1 + \left[\gamma_{\max 1}(\gamma_{\max 1} - 1) \frac{\pi n_{r1} \omega_1^2}{\lambda L} \right]^2 \right\}^{-1} \tag{15}$$

$$T_{B2} = \left\{ 1 + \left[\gamma_{\max 2}(\gamma_{\max 2} - 1) \frac{\pi n_{r2} \omega_2^2}{\lambda L} \right]^2 \right\}^{-1} \tag{16}$$

In Equations (13)–(16), index 1 stands for the parameters for an input fiber (type G.655) and index 2 for an output fiber (type G.652), Fig. 9. Figure 10 shows loss of

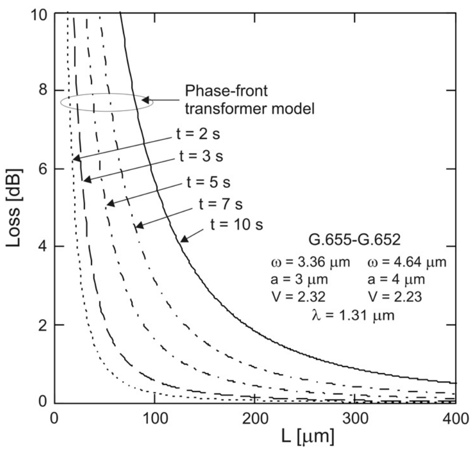

Fig. 10. Loss of TEC areas as a function of length L for joining fibers of G.655, G.653 and G.652 type – phase front transformer model $\lambda = 1.31$ μm.

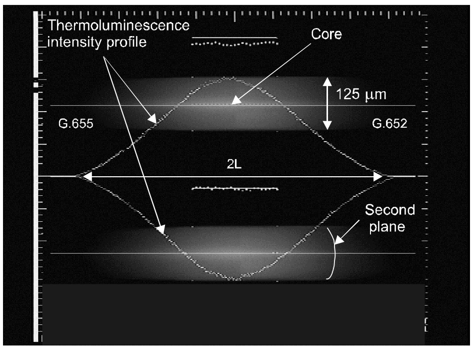

Fig. 11. Example of thermoluminescence intensity profile of fusion spliced fibers G.652 and G.655.

TEC areas for connecting fibers of G.652 and G.655 types at five thermal connecting times ensuring good match of mode fields, *i.e.*, 2, 3, 5, 7 and 10 seconds.

From the results presented in Fig. 10 it follows that neglecting the mode field matching, the shortest the diffusion time, the smaller the TEC area loss.

Length $2L$ of the TEC area during optimization of the splicing process (splicer Ericsson FSU 925TC) was evaluated on the basis of thermoluminescence of the spliced fibers. Figure 11 presents a thermoluminescence intensity profile, along the cores, of the fusion spliced fibers G.652 and G.655. The splicing temperature in the center was $T \approx 2000$ °C, splicing time $t_2 = 3$ s. The temperature was decreasing from the splice center until it reached room temperature, where the thermoluminescence line changes into a horizontal one from the left- to the right-hand side of the splice. The distance which can be identified as $2L$ is 675 μm and is considerably longer than L_c, Tab. 5. Thus, the phase-front transformer model is justified in this case.

T a b l e 6. Values of T_f (12) and loss $-10\log T_f$ for $2L = 675$ μm, $\lambda = 1.31$ μm and $\lambda = 1.55$ μm.

Diffusion time [s]	T_f ($\lambda = 1.31$ μm)	$-10\log T_f$ ($\lambda = 1.31$ μm) [dB]	T_f ($\lambda = 1.55$ μm)	$-10\log T_f$ ($\lambda = 1.31$ μm) [dB]
2	0.995	0.022	0.993	0.031
3	0.989	0.048	0.983	0.074
5	0.964	0.159	0.951	0.218
7	0.926	0.334	0.899	0.462
10	0.852	0.696	0.801	0.964

T a b l e 7. Values of A_Σ for $\lambda = 1.31$ μm and $\lambda = 1.55$ μm.

Diffusion time [s]	A_Σ ($\lambda = 1.31$ μm) [dB]	A_Σ ($\lambda = 1.55$ μm) [dB]
2	0.070	0.084
3	0.058	0.087
5	0.163	0.220
7	0.362	0.486
10	0.768	1.027

Values of T_f (12) and loss $-10\log T_f$ [dB] for this length and for splicing times of 2–10 seconds and $\lambda = 1.31$ μm and $\lambda = 1.55$ μm, respectively, are presented in Tab. 6.

Total losses of the TEC area are the sum of losses due to the mismatch of mode field radii and losses resulting from transmission. In Table 7, summary losses

$$A_\Sigma = -10\log\left[\left(\frac{2\,\omega_{\mathrm{diff1}}\,\omega_{\mathrm{diff2}}}{\omega_{\mathrm{diff1}}^2 + \omega_{\mathrm{diff2}}^2}\right)^2\right] - 10\log T_f$$

for the assumed by the author diffusion times are presented.

Theoretical calculations presented in Fig. 10 and Tab. 7 confirmed data from [1, 17], where diffusion times were matched experimentally, that optimal fusion times for connecting fibers with parameters such as fibers of the type G.652 and G.655 at $T \approx 2000$ °C are times ranging from 2 to 5 seconds. At the same time it should be noted that the increase of thermal connecting loss with the diffusion time (within rational limits) is mainly due to transmission properties of the TEC area rather than mismatch of the spliced fiber mode field radii.

Consideration similar as for the TEC linear areas can be given to areas with Gaussian refractive index distribution in the fibers and along TEC. Gaussian distribution assumption leads to slightly smaller loss T_f of the TEC area –

propagation beam model [5] which does not change but rather confirms the above presented results and conclusions.

4. Conclusions

In the process of thermal fiber connecting there occurs the core dopant diffusion. The consistence of the dopant diffusion and Gaussian distributions was found the better the longer the diffusion time (thermal connecting) and the better the consistence. Thus, the dopant diffusion distributions and in effect the refractive index profile can be approximated with Gaussian distributions. Gaussian field distribution approximation which significantly simplifies calculation of losses due to the mismatch of mode field radii of the spliced fibers is specially useful in those cases of refractive index profiles for which there is no analytic scalar wave equation solution. Gaussian refractive index profile is such an example. This form of profile is of great importance from the practical point of view as, first, it reflects dopant diffusion processes between the core and cladding in the fiber production process, second, it can be used for approximation of refractive index in the transit areas of thermally connected telecommunication fibers of different types. In so connected fibers it is possible, thanks to proper dopant diffusion, to achieve a thermally expanded-core transit (TEC) area and join fibers with different values and refractive index coefficients almost without any losses.

The above theoretical analysis of the TEC transmission area properties showed that it is possible to achieve loss below 0.1 dB for a thermal joint (splice) of fibers such as: G.652 and G.655, whose parameters differ significantly. The results of analysis are consistent with experimental data obtained by the author.

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